

Pair Creation by Very High Energy Photons in Gamma-Ray Bursts: A Unified Picture for Various Energetics of GRBs

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ABSTRACT

The extreme energetics of the gamma-ray burst (GRB) 990123 has revealed that some of GRBs emit quite a large amount of energy, and total energy release from GRBs seems to change from burst to burst by a factor of 10^2 – 10^3 as $E_{\gamma,\text{iso}} \sim 10^{52-55}$ erg, where $E_{\gamma,\text{iso}}$ is the observed GRB energy when radiation is isotropic. If all GRBs are triggered by similar events, such a wide dispersion in energy release seems odd. Here we propose a unified picture for these various energetics of GRBs, in which all GRB events release roughly the same amount of energy of $E_{\text{iso}} \sim 10^{55-56}$ erg as relativistic motion, with the baryon load problem almost resolved. A mild dispersion in the initial Lorentz factor (Γ) results in difference of $E_{\gamma,\text{iso}}$ up to a factor of $m_p/m_e \sim 10^3$. Protons work as “a hidden energy reservoir” of the total GRB energy, and $E_{\gamma,\text{iso}}$ depends on the energy transfer efficiency from protons into electrons (or positrons) in the internal shock. We show that this transfer occurs via e^\pm pair-creation by very high energy photons of proton-synchrotron radiation, and this efficiency depends quite sensitively on Γ . We also show that, in spite of the wide dispersion in $E_{\gamma,\text{iso}}$, this model predicts roughly a constant photon energy range of the e^\pm -pair synchrotron at \sim MeV, which is well consistent with GRB observations. The optical flash of GRB 990123 can be explained by the internal shock origin in our model. The apparent no-correlation between $E_{\gamma,\text{iso}}$ and observed afterglow luminosity is consistent with the expectation of our scenario.

Key words: acceleration of particles — gamma-rays: bursts — gamma-rays: theory

1 INTRODUCTION

Gamma-ray bursts (GRBs) are known as an explosive phenomenon occurring at cosmological distances ($z \gtrsim 1$), emitting an extremely large amount of energy ($E_{\gamma,\text{iso}} \gtrsim 10^{51-52}$ erg, when radiation is isotropic) mostly in the soft γ -ray range of keV–MeV (see, e.g., Piran 1999 for a review). However, recent observations revealed that some of GRBs are emitting an even larger amount of energy with $E_{\gamma,\text{iso}} \gg 10^{52}$ erg. For GRBs 971214 and 980703, their total energies were estimated from redshifts of identified host galaxies as $E_{\gamma,\text{iso}} \sim 3 \times 10^{53}$ and 2×10^{53} erg, respectively (Kulkarni et al. 1998; Djorgovski et al. 1998). Recently GRB 990123 further pushed up the total energy to $E_{\gamma,\text{iso}} \gtrsim 3 \times 10^{54}$ erg ($\approx 1.7M_\odot c^2$), whose redshift was estimated as $z = 1.60$ from absorption lines observed in its optical afterglow (Kulkarni et al. 1999). It has also been suggested that GRB 980329 might have emitted $E_{\gamma,\text{iso}} \gtrsim 10^{54}$ erg, if the redshift of this GRB is $z \sim 5$ as inferred from the possible Lyman break observed in the spectrum of its optical afterglow (Fruhster 1999). On the other hand, there are less energetic bursts,

such as GRB 970508 whose total energy is $E_{\gamma,\text{iso}} \sim 7 \times 10^{51}$ erg (Metzger et al. 1997). Hence, it is now confirmed that total energy emitted from GRBs is broadly distributed with a wide dispersion by a factor of $\sim 10^2$ – 10^3 , in spite of the roughly constant photon energy range of γ -rays.

Currently the most popular explanation for the GRB phenomenon is dissipation of the kinetic energy of ultra-relativistic bulk motion with a Lorentz factor of $\Gamma \gtrsim 10^2$ –3, in internal shocks which are generated by relative velocity difference of relativistic shells ejected from a central engine (e.g., Piran 1999; see also Fenimore et al. 1999b and Sari & Piran 1999 for recent arguments preferring the internal shock scenario to the alternative external shock). All the total energy ejected as relativistic bulk motion cannot be dissipated in internal shocks, and hence the total energy truly emitted as kinetic motion (E_{iso}) should be larger than the observed $E_{\gamma,\text{iso}}$, at least by a factor of several. Therefore, some of GRBs must emit quite a large amount of energy, $E_{\text{iso}} \gtrsim 10^{55}$ erg.

There are accumulating evidences for GRBs occurring mostly in star forming regions of distant galaxies (e.g.,

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Paczynski 1998; Kulkarni et al. 1998; Bloom et al. 1999), and it suggests that GRBs are related to cataclysmic death of massive stars, such as gravitational collapses or mergers of compact objects. However, if this is the case, it seems somewhat odd that the total energy emitted from GRBs shows such a wide dispersion. It may rather be natural to consider that all GRBs emit roughly the same amount of energy with $E_{\text{iso}} \sim 10^{55-56}$ erg, and another physical process is responsible for the dispersion in the γ -ray efficiency ($E_{\gamma,\text{iso}}/E_{\text{iso}}$), producing a dispersion in $E_{\gamma,\text{iso}}$ by a factor of $\sim 10^3$. Because of the extremely large amount of energy emitted by GRB 990123, a strong beaming of γ -ray emission is now discussed intensively (e.g., Kulkarni et al. 1999). It is possible that the energy release from GRB events is roughly the same for all bursts but the beaming factor significantly changes from burst to burst, resulting in the wide dispersion in $E_{\gamma,\text{iso}}$. However, there is no plausible reason why the beaming factor changes by a factor of $\sim 10^3$ from burst to burst, and other explanations may be favorable in which a relatively small dispersion of a physical parameter of GRBs results in a factor of $\sim 10^3$ dispersion in $E_{\gamma,\text{iso}}$. In this letter we propose such a model, in which the factor of $\sim 10^3$ is understood roughly as the proton-electron mass ratio and difference in Γ by a factor of $\sim 3-4$ is the origin of the dispersion in $E_{\gamma,\text{iso}}$. All GRBs emit the total energy of $E_{\text{iso}} \sim 10^{55-56}$ erg with roughly the same beaming factor. (Therefore, if GRBs are generated from objects with stellar masses, a strong beaming with a factor of $b \equiv (4\pi/\Delta\Omega) \gtrsim 10^2$ is highly likely.)

Since the origin of the GRB energy is relativistic bulk motion, protons should carry a much larger amount of energy than electrons by a factor of $m_p/m_e \sim 2,000$, at least in the initial stage of the internal shock generation. It is uncertain what fraction of the proton energy is converted into electrons, but the simplest Coulomb interaction cannot transfer the proton energy into electrons within the time scale of GRBs, as will be shown in this letter. The soft γ -rays are generally considered to be generated by electrons, because of the short time variability of GRBs. Therefore it is not unreasonable that, in some GRBs, only 1/2000 of E_{iso} is carried by electrons and then emitted as soft γ -rays. On the other hand, it may also be possible that a physical process works as an energy conveyor from the hidden energy reservoir (i.e., protons) into electrons (or positrons). If the energy transfer is almost complete for a GRB, a significant fraction of E_{iso} can be radiated as soft γ -rays. In our scenario, the energy conveyor is e^\pm pair-creation in internal shock by very high energy photons radiated by proton-synchrotron. We will show that the energy transfer efficiency by this process is quite sensitively dependent on Γ , and hence a relatively small difference in Γ from burst to burst gives a large dispersion in $E_{\gamma,\text{iso}}$. We will also show that the observed photon energy range of the e^\pm -pair synchrotron is roughly constant at \sim MeV range, in spite of the large dispersion in $E_{\gamma,\text{iso}}$. This gives an explanation for the universal photon energy range of GRBs. Otherwise, the photon energy range of \sim MeV is difficult to explain by the internal shock scenario with equipartition magnetic fields, in which the typical Lorentz factor of particles is Γ^{-1} times smaller than that in external forward shocks.

2 PAIR-CREATION IN INTERNAL SHOCKS

In the following we consider the energy transfer from protons into electrons (or e^\pm pairs) to be observed as soft γ -rays, by using a simple model. The basic model parameters are the following three: E_{iso} , Γ , and the duration of GRBs (T). We use the natural units with $c = \hbar = 1$ throughout this letter. If the energy emission from the central engine is continuous, the duration of energy emission is the same with the observed GRB duration. If the Lorentz factor of emitted matter has a dispersion of $\Delta\Gamma \sim \Gamma$, faster ejecta will catch up with the slower ones and hence internal shocks are generated at a radius $R \sim \Gamma^2 T$. The energy density at the shock rest is given as $\rho_{\text{rest}} \sim \rho_{\text{lab}} \Gamma^{-2} \sim E_{\text{iso}}/(4\pi R^2 T \Gamma^2)$, where ρ_{lab} is the energy density measured in the laboratory frame. The shock Lorentz factor is of order unity in the internal shock, and hence the typical Lorentz factor of protons at the shock rest is also $\gamma_p \sim 1$. Hence, the particle number density at the shock frame is given by $n_p \sim n_e \sim \rho_{\text{rest}}/m_p$.

First we show that the Coulomb interaction cannot transport the energy carried by protons into electrons to achieve energy equipartition. The time scale of energy transfer in relativistic plasma is roughly given by $\tau_{ep} \sim (n_p \sigma_t)^{-1}$, where $\sigma_t = 4\pi L_e (e^2/m_e \gamma_e)^2$ is the transport cross section for electron-proton collisions and γ_e is the electron Lorentz factor at the shock rest. The Coulomb logarithm is given by $L_e = \ln(am_e \gamma_e)$, where $a = (m_e \gamma_e / 4\pi n_e e^2)^{1/2}$ is the Debye length (e.g., Lifshitz & Pitaevskii 1981). For typical parameters, $L_e \sim 40$. This time scale should be compared with the expansion time measured in the shell frame, $t_{\text{exp}} = R/\Gamma$, and we find $\tau_{ep}/t_{\text{exp}} = 9.3 \times 10^6 (\gamma_e/10^3)^2 E_{56}^{-1} \Gamma_{300}^5 T_{30}^2 L_{40}^{-1}$, where $\Gamma_{300} = \Gamma/300$, $E_{56} = E_{\text{iso}}/(10^{56} \text{ erg})$, $T_{30} = T/(30 \text{ sec})$, and $L_{40} = L_e/40$. In order for the energy equipartition between protons and electrons, γ_e should become $\sim m_p/m_e \sim 10^3$, but this equation shows that the time scale of the Coulomb interaction is too long to achieve the equipartition. Hence it is reasonable to suppose that protons carry a much larger amount of energy than electrons by a factor of $\sim 10^3$.

Next we consider the synchrotron emission of protons. Proton synchrotron is generally quite inefficient due to its quite long time scale, but Totani (1998a, b) has shown that, when E_{iso} is as large as $\sim 10^{55-56}$ erg, proton cooling time becomes comparable with the GRB duration at the acceleration maximum ($\sim 10^{20}$ eV). Therefore if the energy spectrum of protons is harder than the typical shock acceleration spectrum, $dN_p/d\gamma_p \propto \gamma_p^{-2}$, a considerable fraction of the total energy can be radiated in the TeV range by synchrotron radiation of protons accelerated to $\sim 10^{20}$ eV. We assume that there is a magnetic field in the internal shock roughly in equipartition with the turbulent energy density, i.e., $B^2/(8\pi) = \xi_B \rho_{\text{rest}}$, where ξ_B is a parameter of order unity for the degree of equipartition. It is generally believed that the time scale of shock acceleration is given by $t_{\text{acc}} = 2\pi\eta r_L$, where $r_L = m_p \gamma_p / (eB)$ is the Larmor radius and η is a parameter of order unity (e.g., de Jager et al. 1996). For the condition that the maximum proton energy is constrained by the synchrotron cooling, a relation, $t_{\text{acc}} = t_{\text{cool}} < t_{\text{exp}}$, must hold at the maximum proton energy, where $t_{\text{cool}} = 6\pi m_p^3 / (\sigma_T m_e^2 B^2 \gamma_p)$ is the proton-synchrotron cooling time at the shock frame. The maximum of γ_p is determined by $t_{\text{acc}} = t_{\text{cool}}$, as

$\gamma_{p,\max} = (3em_p^2/\sigma_T m_e^2 B\eta)^{1/2}$, and with this $\gamma_{p,\max}$ we can check that the condition $t_{\text{cool}} \lesssim t_{\text{exp}}$ actually holds:

$$\frac{t_{\text{cool}}}{t_{\text{exp}}} = 0.41\eta^{1/2}\xi_B^{-3/4}E_{56}^{-3/4}\Gamma_{300}^{7/2}T_{30}^{5/4}, \quad (1)$$

with reasonable GRB parameters.

Hence the energy carried by protons with $\gamma_p \sim \gamma_{p,\max}$ can efficiently be radiated within the GRB duration. The synchrotron photon energy at the shock rest is given by $\varepsilon_{\text{rest}} = \gamma_p^2 eB/m_p$, and then one can show that the maximum synchrotron photon energy corresponding to $\gamma_{p,\max}$ does not depend on B and is expressed only by fundamental constants, i.e., $\varepsilon_{\text{max,rest}} \sim 3e^2 m_p/(\sigma_T m_e^2 \eta) = 46\eta^{-1}$ GeV. In the following we suggest that this universal value is responsible for the universality of the observed photon energy range of GRBs. The maximum synchrotron photon energy for observers is then $\varepsilon_{\text{max,obs}} \sim 14\eta^{-1}\Gamma_{300}$ TeV, and this radiation gives an explanation (Totani 1998b) for the possible detections of GRBs above 10 TeV reported by the Tibet (Amenomori et al. 1996) and the HEGRA (Padilla et al. 1998) groups.

For a typical spectrum of accelerated particles, the luminosity (νF_ν) of synchrotron radiation becomes maximum at the maximum photon energy. Therefore, energy carried by protons is most efficiently radiated at around $50\eta^{-1}$ GeV at the shock rest. However, it must be checked whether these high energy photons can escape freely from internal shocks. Photons with $\sim 50\eta^{-1}$ GeV interact most efficiently with low energy photons at $2m_e^2/(50\eta^{-1}\text{GeV}) \sim 10\eta$ eV, via the $\gamma\gamma \rightarrow e^\pm$ reaction whose cross section is roughly given by the Thomson cross section σ_T . Hence radiation observed as $\sim 3\Gamma_{300}\eta$ keV photons produced by electron synchrotron radiation in the internal shock could be a significant absorber of the very high energy photons. Electrons carry about (m_e/m_p) of the total energy, and suppose that a fraction ζ of the total electron energy is converted into target photons with restframe energy around $\varepsilon_{t,\text{rest}} \sim 10\eta$ eV. The column density of the low energy target photons then becomes

$$N_\gamma \sim \frac{\zeta E_{\text{iso}} m_e}{4\pi R^2 m_p \Gamma \varepsilon_{t,\text{rest}}}. \quad (2)$$

Then the opacity of very high energy photons is given as $\tau_{\gamma\gamma} \sim \sigma_T N_\gamma \sim 0.9\zeta_{-2} E_{56} T_{30}^{-2} \Gamma_{300}^{-5} \eta^{-1}$, where $\zeta_{-2} = \zeta/10^{-2}$. We will discuss the value of ζ and electron synchrotron radiation in more detail in §3.

It should be noted that $\tau_{\gamma\gamma}$ is of order unity, and also quite sensitively depends on Γ . When $\Gamma \sim 300$, most of proton-synchrotron photons create e^\pm pairs due to the optical depth of order unity. Therefore energy conversion from protons into e^\pm pairs is efficient, and synchrotron radiation of the created pairs produces the energetic GRBs such as GRB 990123 or 980329. On the other hand, with increasing Γ above ~ 300 , the energy transfer into e^\pm pairs becomes rapidly inefficient, because $\tau_{\gamma\gamma}$ decreases as $\propto \Gamma^{-5}$, and also because the proton acceleration becomes limited by the expansion time, rather than the synchrotron cooling (see eq. 1). In this case $E_{\gamma,\text{iso}}$ is expected to be much smaller than E_{iso} , down to $\sim (m_e/m_p)E_{\text{iso}}$ which is the energy released by the original electron synchrotron. A modest variation in Γ (\sim a factor of 3–4), which is necessary for the internal shock scenario of GRBs, will result in difference of $\tau_{\gamma\gamma}$ by a

factor of $\sim 10^3$, and hence explains the observed dispersion in $E_{\gamma,\text{iso}}$.

Then our next interest is whether the created pairs produce the soft γ -rays as observed, in the correct photon energy range. From energy conservation, it is clear that each of created pairs has roughly a half of the energy of very high energy photons ($\sim 50\eta^{-1}$ GeV), and hence the Lorentz factor of pairs in the shock rest is typically $\gamma_\pm \sim 50\eta^{-1}\text{GeV}/(2m_e) \sim 4.9 \times 10^4 \eta^{-1}$. The observed pair-synchrotron photon energy is given by $\varepsilon_{\text{obs}} = \Gamma\gamma_\pm^2 eB/m_e = 5.1\eta^{-2}\Gamma_{300}^{-2}\xi_B^{1/2}E_{56}^{1/2}T_{30}^{-3/2}$ MeV. Considering the simplicity of the model, this photon energy is well consistent with the observed νF_ν peaks of GRBs at around 0.1–1 MeV (e.g., Mallozzi et al. 1995), and hence this peak can be interpreted as the synchrotron photon energy corresponding to the typical energy of created pairs. The νF_ν peak depends relatively weakly on Γ , because of the universal value of the maximum proton-synchrotron photon energy. A dispersion by a factor of ~ 3 –4 in Γ would produce change in the νF_ν peak at most a factor of 10, which is consistent with the observation (Mallozzi et al. 1995). Therefore, we have successfully explained the fact that $E_{\gamma,\text{iso}}$ changes almost by a factor of 10^3 from burst to burst, while the photon energy range of GRBs shows little change.

3 ELECTRON SYNCHROTRON AND OPTICAL FLASH

Here we consider the synchrotron radiation of electrons which are originally loaded in the ejected matter (i.e., not created pairs). These electrons must produce the target photons which interact with the very high energy proton-synchrotron photons. The shock Lorentz factor in internal shocks is of order unity, and hence the minimum Lorentz factor of electrons at the shock rest is $\gamma_e \sim 1$, because there is almost no energy transfer from protons into electrons in our scenario. In this case, the observed electron-synchrotron radiation starts at a very low photon energy of

$$\varepsilon_{\gamma,\text{obs}} = \Gamma\gamma_e^2 eB/m_e \sim 2.1 \times 10^{-3} \gamma_e^2 \Gamma_{300}^{-2} \xi_B^{1/2} E_{56}^{1/2} T_{30}^{-3/2} \text{ eV}. \quad (3)$$

The synchrotron cooling time of electrons for observers is $t_{\text{obs}} = t_{\text{rest}}/(2\Gamma)$, where $t_{\text{rest}} = 6\pi m_e/(\sigma_T B^2 \gamma_e)$ is the cooling time at the shock frame. Comparing the cooling time for observers with the GRB duration (T), we find that the electron synchrotron is in the efficient cooling regime above an observed photon energy of $\varepsilon_{\text{cl}} = 2.8 \times 10^{-5} \xi_B^{-3/2} E_{56}^{-3/2} \Gamma_{300}^8 T_{30}^{5/2}$ eV. The synchrotron self-absorption should also be taken into account. By using the previously estimated electron number density and magnetic fields in the internal shock, the optical depth ($\tau_{\text{syn}} \sim \chi TT$) of the synchrotron self-absorption can be estimated (e.g., Longair 1994), where χ is the absorption coefficient of the self-absorption and TT is the shell thickness measured in the shock frame. From this optical depth, we find that the synchrotron radiation becomes optically thin above an observed photon energy of $\varepsilon_{\text{ab}} = 5.6\tau_{\text{syn}}^{-1/3} \xi_B^{1/3} \gamma_{e,\text{min}}^{1/3} E_{56}^{2/3} T_{30}^{-5/3} \Gamma_{300}^{-8/3}$ eV, where we have assumed that the spectrum of electrons as $dN/d\gamma_e \propto \gamma_e^{-2}$ and $\gamma_{e,\text{min}}$ is the minimum value of γ_e . Therefore efficient electron-synchrotron emission starts at the optical band, where emission is marginally optically thin

depending the model parameters. The energy of target photons for the very high energy proton-synchrotron photons is $\sim 3\Gamma_{300}\eta$ keV for observers, and in this band the radiation is optically thin and in the efficient cooling regime. Therefore most of energy carried by electrons corresponding to the target photon energy is converted into the target photons. The energy fraction of such electrons in the total electron energy depends on the acceleration spectrum, and $\zeta \sim 10^{-2}-10^{-1}$ might be a plausible value.

It should be noted that the electron-synchrotron radiation extends to lower photon energies of the optical range. The optical flash observed for GRB 990123 (Akerlof et al. 1999) can be attributed to this internal shock origin, although this does not reject the explanation by reverse shocks (Sari & Piran 1999; Mészáros & Rees 1999). The peak optical flux of 5×10^{49} erg s $^{-1}$ and the flash duration of ~ 50 sec suggest that the energy emitted as the optical flash is about $E_{\text{opt,iso}} \sim 10^{51}$ erg, which is about 10^3 times smaller than the energy emitted as γ -rays. In our scenario, this difference can be understood roughly as the proton-electron mass ratio, because the optical flash is synchrotron radiation of electrons originally loaded in the internal shock matter, while γ -rays are synchrotron radiation of created e^\pm pairs which possess a significant fraction of energy originally carried by protons.

This scenario predicts that the total energy emitted as optical flashes is roughly constant at $E_{\text{opt,iso}} \sim 10^{51-52}$ erg, while $E_{\gamma,\text{iso}}$ considerably changes from burst to burst due to different efficiencies of e^\pm creation. This trend is different from that in other GRB models which predict a rough scaling of γ -ray/optical fluence, and hence future observations may discriminate these different scenarios. In fact, the observed correlation between $E_{\gamma,\text{iso}}$ and γ -ray/X-ray peak flux ratio (Norris, Marani, & Bonnell 1999) may already suggest this trend. Our scenario predicts that variation in X-ray luminosity is also small compared with that in γ -ray luminosity, because the synchrotron radiation of created pairs is radiated mainly in the γ -ray range, as we have shown. Therefore γ /X ratio should increase with $E_{\gamma,\text{iso}}$. For the five GRBs with redshift information (including GRB 980329), $E_{\gamma,\text{iso}} = 0.55, 11, 26, 110, 330 \times 10^{52}$ erg for GRBs 970508, 980703, 971214, 980329, and 990123, respectively. [Here and in the following we assume the cosmological parameters as $(h, \Omega_0, \Omega_\Lambda) = (0.7, 0.3, 0.7)$.] The γ /X peak flux ratio for these GRBs is 25, 40, 56, 120, and 252 in the same order (Norris et al. 1999). Although scatter is considerable, such a trend is clearly seen. The γ /X ratio does not increase in proportion to $E_{\gamma,\text{iso}}$, and this can be understood by the contamination of pair-synchrotron radiation in the X-ray band. The cooling time of pairs is much shorter than the GRB duration, and synchrotron photon energy should decrease with the cooling of pairs, making some contribution in the X-ray band.

Similarly our model predicts that the energy emission from afterglows is not correlated with $E_{\gamma,\text{iso}}$, because roughly the same amount of energy $\sim E_{\text{iso}}$ is injected into interstellar matter for all GRBs regardless of the pair-creation efficiency. We note that such a trend has already been seen in the flux ratio of GRBs and optical afterglows. We can estimate a characteristic amount of energy emitted from afterglows, as $E_R(t) \equiv \nu_R L_\nu(\nu_R)t$, where ν_R is the R-band frequency, L_ν the afterglow luminosity per unit fre-

quency, t the time from the burst, and all these quantities are those measured in the rest frame of a host galaxy. By using the observed R-band light curves (Pian et al. 1998; Kulkarni et al. 1998; Galama et al. 1999), we have estimated E_R for the famous three GRBs with known redshifts: $E_R(1\text{day}) = 4.2, 0.9$, and 1.2×10^{49} ergs for GRB 970508, 971214, and 990123, respectively. Here we have assumed the spectrum and time evolution of afterglows as $f_\nu \propto t^{-\alpha} \nu^{-\beta}$, with $(\alpha, \beta) = (1.1, 0.7)$ which are typical values for GRB afterglows, to take into account the K-correction and cosmological time dilation. Clearly there is almost no correlation between $E_{\gamma,\text{iso}}$ and afterglow luminosity, and the latter seems rather uniform. Such a trend is consistent with the expectation of our model.

4 STRUCTURE OF THE EMISSION REGION IN INTERNAL SHOCKS

In this section we consider the size of emission region where created e^\pm pairs are injected, and we show that such emitting regions are likely to be clumpy. Once pair creation by very high energy photons starts at a seed region, created pairs radiate photons mainly in the observer's soft γ -ray band, but also radiate lower-energy target photons at \sim keV when the Lorentz factor of pairs decreases due to cooling. Increase of target photons will be followed by more efficient pair creation, and then be followed again by increase of target photons. Therefore perturbation in local pair-creation rate will unstably grow to a clumpy structure of γ -ray emitting region. The created pairs cannot freely expand by the speed of light, but they are trapped around the seed region due to magnetic fields. This picture is very similar to "the seed growth scenario" discussed in Fenimore et al. (1996), and it may give an explanation for the very low surface filling factor of GRBs (Fenimore et al. 1996, 1999a). If emission region is homogeneous with a scale of visible shock region, complicated time structure seen in GRB light curves cannot be explained. Rather, only very small fraction (i.e., the surface filling factor) of shocked region can be active for γ -ray emission. It should be noted that, in the internal shock scenario, the stochastic nature of internal shock generation may also provide an origin of the inhomogeneity in the shocked region, resulting in the small filling factor. However, the scale and amplitude of the inhomogeneity of internal shocks are highly uncertain, and our model provides another candidate for the origin of the small filling factor.

It is difficult to theoretically estimate a typical size of pair-creation regions, but the minimum size possible may be estimated by a diffusion process with a mean free path of order the Larmor radius of pairs. The Larmor radius for the typical pair energy of $\sim 25\eta^{-1}$ GeV at the shock rest is $r_L \sim 1.4 \times 10^5 \eta^{-1} \xi_B^{-1/2} E_{56}^{-1/2} \Gamma_{300}^3 T_{30}^{3/2}$ cm. Then the size achieved by a random diffusion process within the restframe expansion time ($t_{\text{exp}} \sim R/\Gamma$) becomes $\Delta r_{\text{em}} \sim (r_L R \Gamma^{-1})^{1/2}$ at the shock rest. The radial size of this emitting region is $\Delta r_{\text{em}}/\Gamma$ in the laboratory frame, and this gives a time scale of a pulse duration as $T_p \sim \Delta r_{\text{em}}/\Gamma$ (e.g., Fenimore et al. 1996). Then we obtain the ratio of a pulse width to the total duration as $T_p/T = (r_L/RT)^{1/2} \sim 2.2 \times 10^{-5} \eta^{-1/2} \xi_B^{-1/4} E_{56}^{-1/4} \Gamma_{300} T_{30}^{1/4}$. Although this estimate may be too simple, this is sufficiently

small to explain the complicated time structure seen in long-duration GRBs.

Each pair-creation region makes a strong pulse in the GRB light curve. If only one of such pulses has a peak flux above a detection threshold of a detector, the observed duration of GRBs will be much shorter than the true duration T . This may be responsible for the bimodal distribution of the observed GRB durations (Kouveliotou et al. 1993). The short duration peak may correspond to a typical size of a pair-creation region, while the long duration peak corresponds to the energy-emission time scale from the central engine.

We speculate that GRBs with complicated time structure are those in which the pair-creation process is efficient (and hence energetic), while GRBs with smooth structure, such as “FRED” GRBs (Fast Rise and Exponential Decay, see, e.g., Fenimore et al. 1996), are those with inefficient pair creation process (and hence less energetic). Norris et al. (1999) reported that there is a correlation between $E_{\gamma, \text{iso}}$ and time lags in energy-dependent light curves of GRBs. Most GRBs show short time lags ($\lesssim 0.1$ sec), and energetic GRBs such as GRB 980329 or 990123 fall in this category. On the other hand, a fraction of GRBs including less energetic bursts such as GRB 970508 show longer time lags (Norris et al. 1999, see also Band 1997). The energy dependent time lags can be understood by delayed arrivals of lower energy photons from off-axis regions compared with the hard onset of a pulse on the line-of-sight to the source (Norris et al. 1999). Therefore, the time lags are expected to increase with the surface filling factor. In our scenario, energetic GRBs in which the pair creation is the dominant process of γ -ray emission should show smaller time lags, because each emission region is very compact compared with the size of internal shocks. In less energetic bursts, synchrotron radiation by originally loaded electrons becomes more significant due to inefficient pair creation, and relatively homogeneous distribution of original electrons will emit γ -rays with longer time scales. We suggest that this may be the origin of the correlation observed by Norris et al. (1999).

5 DISCUSSION

In this letter we have suggested that not only GRB 990123, but also all GRBs emit a large total energy of $E_{\text{iso}} \gtrsim 10^{55}$ erg. We note that the baryon load problem, which has been a quite difficult problem for a long time in theoretical modeling of GRBs, is considerably relaxed. The baryon mass which should be loaded in the relativistic bulk motion is $m_{\text{iso}} \sim E_{\text{iso}}/\Gamma \sim 0.2E_{56}\Gamma_{300}^{-1}M_{\odot}$ for 4π steradian. This value is still small, but seems not unreasonable in stellar death models. On the other hand, if we consider the conventional energy scale of $E_{\text{iso}} \sim 10^{52}$ erg, immediately we come up against the unreasonably small baryon load of $m_{\text{iso}} \sim 10^{-5}M_{\odot}$. Therefore our scenario makes the theoretical modeling of GRBs considerably easier in a sense that the baryon load problem is almost resolved, although the energy release required is quite large and a strong beaming is necessary for stellar death models.

Brainerd (1998a, b) argued that the total energy released by GRB 970508 should be much larger than that observed as γ -ray fluence, if the radio afterglow of this GRB

is optically-thick synchrotron radiation of electrons. This is quite a model-independent argument based on the source size of the radio afterglow ($\sim 3\mu\text{as}$) inferred from the time variability of radio flux due to the scintillation by the interstellar matter within the Galaxy (Frail et al. 1997). This analysis may give a support for our scenario in which the true kinetic energy release of GRB 970508 is the same with GRB 990123.

The time profile of GRB 990123 suggests that the γ -ray emission of GRBs is not the external shock origin (Fenimore et al. 1999b). The advantage of the external forward shock scenario for the γ -ray emission was that typical photon energy range of electron synchrotron is much higher than that in internal or reverse shocks. The shock Lorentz factor of the external forward shock is the same with that of the relativistic bulk motion (Γ), while it is of order unity for the internal or reverse shocks. Therefore, the particle Lorentz factor in external forward shocks is also Γ times larger than that in the internal or reverse shocks, and hence the synchrotron photon energy is Γ^2 times higher than the other two. In fact, as shown in eq. (3), typical photon energy band of electron-synchrotron from internal shocks is much lower than the observed emission band of GRBs ($\sim \text{MeV}$), when typical γ_e is ~ 1 . Even when the energy conversion from protons into electrons is efficient, i.e., $\gamma_e \sim 10^3$, the typical synchrotron photon energy is at most $\sim 10\text{--}100$ eV. (Note that in this case we should use $E_{\text{iso}} \sim E_{\gamma, \text{iso}} \sim 10^{52-53}$ erg for typical GRBs.) If we attribute the optical flash to the reverse or internal shocks (Sari & Piran 1999; Mészáros & Rees 1999), and γ -ray emission is not the external shock origin, we have a difficulty in explaining the typical photon energy of the γ -ray emission of GRBs with equipartition magnetic fields. As we have shown in this letter, the pair creation by very high energy photons of proton-synchrotron provides a promising candidate for the explanation of the γ -ray energy range of GRBs.

The simplest prediction of our scenario is that we should observe a comparable, or even larger amount of energy emission in the TeV range compared with $E_{\gamma, \text{iso}}$, from some fraction of GRBs in which the pair-creation optical depth $\tau_{\gamma\gamma}$ is of order unity or less. On the other hand, when $\tau_{\gamma\gamma} \gg 1$, the TeV flux should be strongly attenuated. Therefore it is difficult to predict the flux ratio between TeV and MeV ranges, and it will considerably change from burst to burst. But if a larger amount of energy emission in TeV range than $E_{\gamma, \text{iso}}$ is observed for a GRB in the future, it would give a strong support for our scenario. Such strong TeV bursts may already have been detected by the Tibet (Amenomori et al. 1996) and the HEGRA groups (Padilla et al. 1998).

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